Journal of Magnetism and Magnetic Materials 324 (2012) 1449–1452

Contents lists available at SciVerse ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Rashba spin–orbit coupling effects on a current-induced domain wall motion

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ARTICLE INFO

Article history:
Received 28 July 2011
Received in revised form
23 November 2011
Available online 9 December 2011

Keywords:
Domain wall motion
Spin–orbit coupling

ABSTRACT

A current-induced domain wall motion in magnetic nanowires with a strong structural inversion asymmetry [I.M. Miron, T. Moore, H. Szambolics, L.D. Buda-Prejbeanu, S. Auffret, B. Rodmacq, S. Pizzini, J. Vogel, M. Bonfim, A. Schuhl, G. Gaudin, Nat. Mat. 10 (2011) 419] seems to have novel features such as the domain wall motion *along the current direction* or the delay of the onset of the Walker breakdown. In such a highly asymmetric system, the Rashba spin–orbit coupling (RSOC) may affect a domain wall motion. We studied theoretically the RSOC effects on a domain wall motion and found that the RSOC, indeed, can induce the domain wall motion along the current direction in certain situations. It also delays the Walker breakdown and for a strong RSOC, the Walker breakdown does not occur at all. The RSOC effects are sensitive to the magnetic anisotropy of nanowires and also to the ratio between the Gilbert damping parameter α and the non-adiabaticity parameter β.

1. Introduction

An electric control of magnetic domain walls(DWs) in a magnetic nanowire has attracted great attention ever since its discovery in 1990s [1,2]. From a number of theoretical [3–9] and experimental [10–16] works, it is well-established that a DW driven by a spin-transfer torque(STT) moves along the electron motion direction. In recent experiments on a current-induced domain wall motion(CIDWM), however, a DW motion *along the current direction* is observed [17–19]. While the DW motion direction in Ref. [17] seems to originate from a negative spin-polarization of injected current pulses and thus can be reconciled with the existing STT theory, results of Refs. [18,19] cannot be fully understood in the scope of the existing STT theory. Other effects on a DW motion such as hydromagnetic drag and Hall charge effects [20] do not seem to explain the experimental results either. Furthermore, considerably high DW velocity due to the delay of the onset of the Walker breakdown [4,8] is observed in Ref. [19]. In Refs. [18,19], highly inversion asymmetric Pt/Co/AlOx nanowires are used to achieve a high STT efficiency. Another recent experiment on a DW motion reports [21] that the inversion symmetry breaking affects a DW velocity. When the inversion symmetry is broken, a Rashba spin–orbit couplig (RSOC) [22] can be induced. Since the SOC affects conduction electron spins, it can alter the direction of local magnetic moments via s-d exchange coupling and thus modify the STT-driven DW dynamics. For a Pt/Co/AlOx film used in Ref. [18,19], the sizable magnitude of the RSOC was reported [23] (the RSOC in Ref. [17] appears to be small since the nanowire structure in Ref. [17] is almost inversion symmetric).

In this report, we investigated the role of the RSOC on a CIDWM. Although there are ongoing efforts to understand how the RSOC affects the CIDWM [24,25], the relevance of the RSOC to a DW motion still remains unclear. Manchon and Zhang reported [24] that the RSOC induces an effective magnetic field but its consequence on the DW motion has not been explored. Obata and Tatara [25] explored the RSOC effects for the special case where the non-adiabaticity parameter β is zero. Here, we extend the previous study to general cases with nonzero β. We find that the RSOC can modify the DW velocity and depending on the ratio between β and the Gilbert damping parameter α, a DW motion *along the current direction* can be observed for a certain current pulse duration time. We also find that the RSOC not only delays the onset of the Walker breakdown, but for the strong RSOC the Walker breakdown cannot occur at all.

2. Theory

When the inversion symmetry is broken, for instance along $\hat{z}$ direction (Fig. 1(a)), the induced RSOC is [22] $H_{SOC} = -i\alpha_R(\nabla \times \hat{z}) \cdot \vec{\sigma}$ where α_R is the RSOC constant. According to Ref. [24], effects of the RSOC on the local magnetization can be taken into account by introducing an effective in-plane field $\vec{H}_R$. When the current of density j is injected in $\hat{x}$ direction, this in-plane field becomes

$$\vec{H}_R = \frac{\alpha_R P}{\mu_B M_S} j(\hat{z} \times \hat{x}), \tag{1}$$

where μ_B is the Bohr magneton, P is the spin-polarization

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doi:10.1016/j.jmmm.2011.12.010

of injected current and M_S is the saturation magnetization. This effective in-plane field is observed in recent experiments on Pt/Co/AlOx nanowires [19,23]. The dynamics of the magnetization $\vec{M}(\vec{r})$ in the presence of the in-plane field $\vec{H}_R$ follows the Landau–Lifshitz–Gilbert equation [4,6]:

$$\frac{d\vec{M}}{dt} = -\gamma\vec{M}\times(\vec{H}_{\rm eff}+\vec{H}_{\rm R})+\frac{\alpha}{M_{\rm S}}\vec{M}\times\frac{d\vec{M}}{dt} -\frac{u}{M_{\rm S}^2}\vec{M}\times\left(\vec{M}\times\frac{\partial\vec{M}}{\partial x}\right)-\frac{\beta u}{M_{\rm S}}\vec{M}\times\frac{\partial\vec{M}}{\partial x}, \tag{2}$$

where γ is the gyromagnetic ratio, $u=(\hbar\gamma/2eM_{\rm S})Pj$ is the magnitude of the STT in a velocity dimension and $\vec{H}_{\rm eff}$ is a total effective magnetic field acting on $\vec{M}(\vec{r})$. $\vec{H}_{\rm eff}$ includes an external magnetic field, magnetic exchange field and anisotropy field. The last two terms of Eq. (2) represent adiabatic and non-adiabatic STT, respectively.

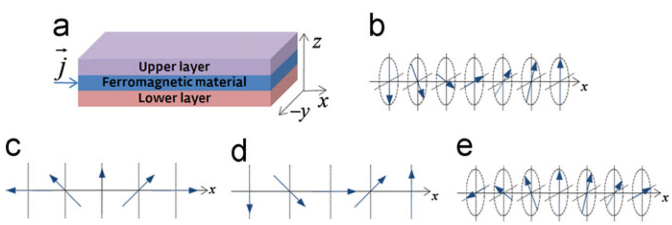

Fig. 1. (a) A film geometry and a coordinate convention. A magnetic configuration of (b) Bloch ($\hat{z}$) wall, (c) Néel ($\hat{x}$) wall, (d) Néel ($\hat{z}$) wall, and (e) Bloch ($\hat{y}$) wall.

Below we derive equations of motion for DW collective coordinates (DW position X and DW tilting angle ψ) from Eq. (2) by using the Thiele's approach [26]. Since the effects of the RSOC are different for different types of DWs, results for each DW configurations are presented.

3. Results and discussion

3.1. Bloch ($\hat{z}$) and Néel ($\hat{x}$) wall

For a Bloch ($\hat{z}$) wall (Fig. 1(b)) which appears in magnetic nanowires with perpendicular magnetic anisotropy (PMA) [17–19,21,23,27], $\vec{H}_{\rm eff}=(2J/M_{\rm S}^2)\nabla^2\vec{M}+(H_{\rm k}M_z/M_{\rm S})\hat{z}-(H_\perp M_x/M_{\rm S})\hat{x}$. Here, J is an exchange coupling constant and $H_{\rm k}$ and $H_\perp$ are the easy and hard axis anisotropy field, respectively. To study the dynamics of collective coordinates, we assume the DW deformation due to the STT and in-plane field is negligible. Then, the magnetic configuration of the DW at $x=X(t)$ is $\vec{M}(\vec{r})=M_{\rm S}(\sin\theta\sin\psi, \sin\theta\cos\psi, \cos\theta)$ where $\cos\theta=\pm\tanh[(x-X)/\lambda]$, $\sin\theta=\mathrm{sech}[(x-X)/\lambda]$ and $\psi=\psi(t)$. Depending on the sign($\pm$), $\vec{M}(\vec{r})$ describes two different types of DWs, where the magnetization changes from $-M_{\rm S}\hat{z}$ to $+M_{\rm S}\hat{z}(+)$ or from $+M_{\rm S}\hat{z}$ to $-M_{\rm S}\hat{z}(-)$ near a DW. Here, $\lambda=\sqrt{2J/H_{\rm k}}$ is the effective DW width. Then,

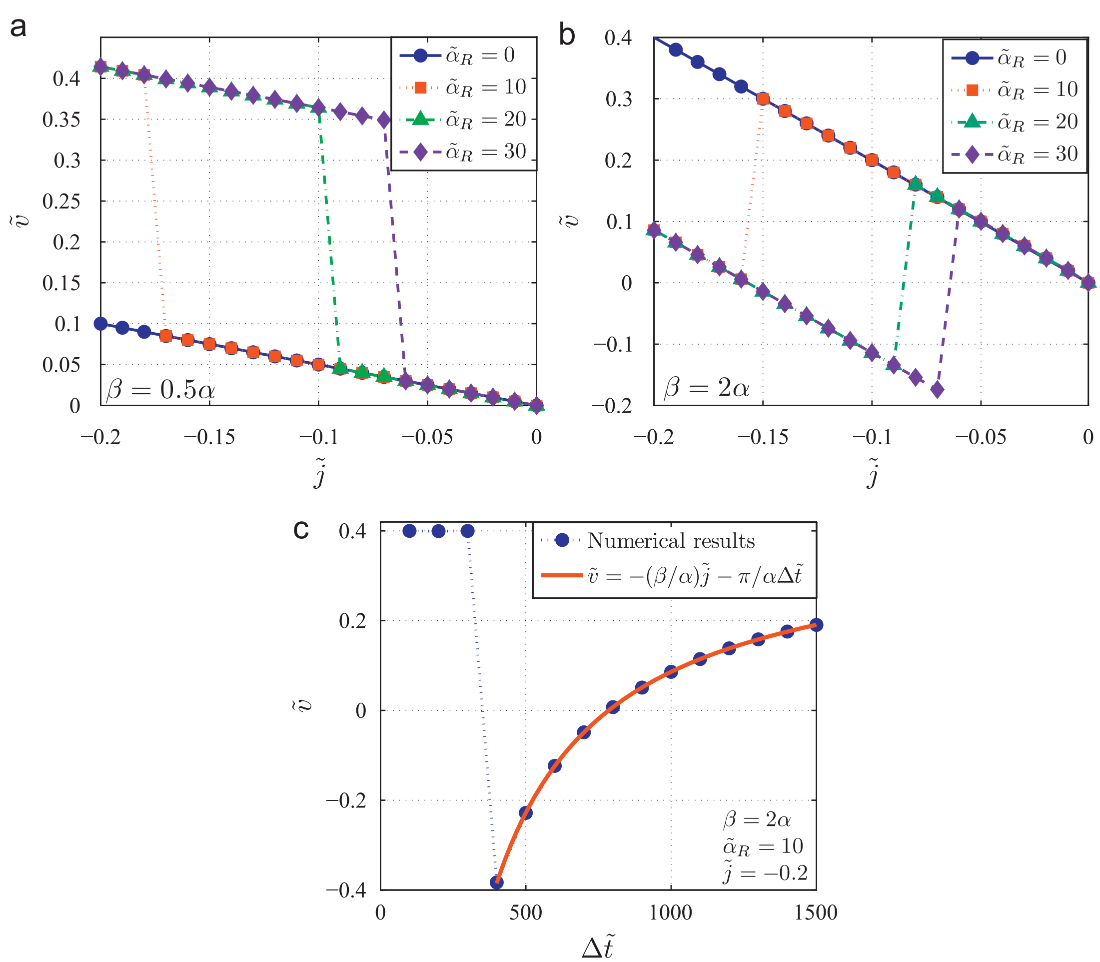

Fig. 2. Average DW velocities $\tilde{v}$ as a function of the current density $\tilde{j}$ (<0) for (a) $\beta/\alpha=0.5$ and (b) $\beta/\alpha=2$. Here, $\Delta\tilde{t}=1000$. Blue circles, red squares, green triangles and purple diamonds represent numerical results for $\tilde{\alpha}_{\rm R}=0$, 10, 20 and 30, respectively. (c) $\tilde{v}$ as a function of a current pulse duration time $\Delta\tilde{t}$ for $\tilde{\alpha}_{\rm R}=10$ and $\tilde{j}=-0.2$. Blue circles are numerical results and a red line represents theoretically predicted values (see text). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)